Thermal analysis and its experimental verification for the present and future IR triplets
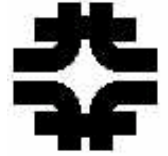
A.V. Zlobin, Fermilab

Workshop on beam generated heat deposition
and quench levels for LHC magnets
3-4 March, 2005
CERN, Switzerland

Outlines

- Introduction
- Temperature profile calculation
  - Model
    - magnet designs and parameters
    - ANSYS thermal model
    - heat depositions
    - material properties and boundary conditions
  - Results
    - 1st generation (NbTi) IRQ
    - 2nd generation (Nb3Sn) IRQ
- Operation margin definition and calculation
- Thermal analysis experimental verification
  - MQXB thermal model (HGQ08)
    - approach
    - results
  - Nb3Sn IRQ thermal model
    - approach
- Conclusions

Introduction
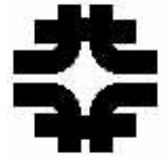
A heat load due to energy depositions of secondary particles coming from IPs will be released in IR quads and in particular in their coils.

The radiation-induced energy deposition will cause a coil temperature rise and (if coil cooling conditions are not sufficient) may lead to premature quench.

To prevent magnet quench the coil temperature (which depends on magnet design, material thermal properties, operation current and temperature, etc.) should be kept below the superconductor critical temperature.

The luminosity upgrade will increase the radiation-induced heat depositions in the magnets increasing the coil local temperatures and the total heat load on the magnet cold mass.

The 1st generation of IR quads based on NbTi superconductor was developed by KEK (MQXA) and FNAL (MQXB) in collaboration with CERN and now is under construction. The work on 2nd generation IR quads based on Nb3Sn superconductor has been started recently in U.S. in the framework of US LHC Accelerator Research Program (LARP). Both generations of IR quads must have the operation margin adequate to the expected radiation heat depositions.

Thermal analysis was performed for NbTi (MQXB) and Nb3Sn IR quads and will be presented here. Results of experimental verification of the thermal calculation for MQXB and possible measurements of operation margin of Nb3Sn IRQ will be also discussed.
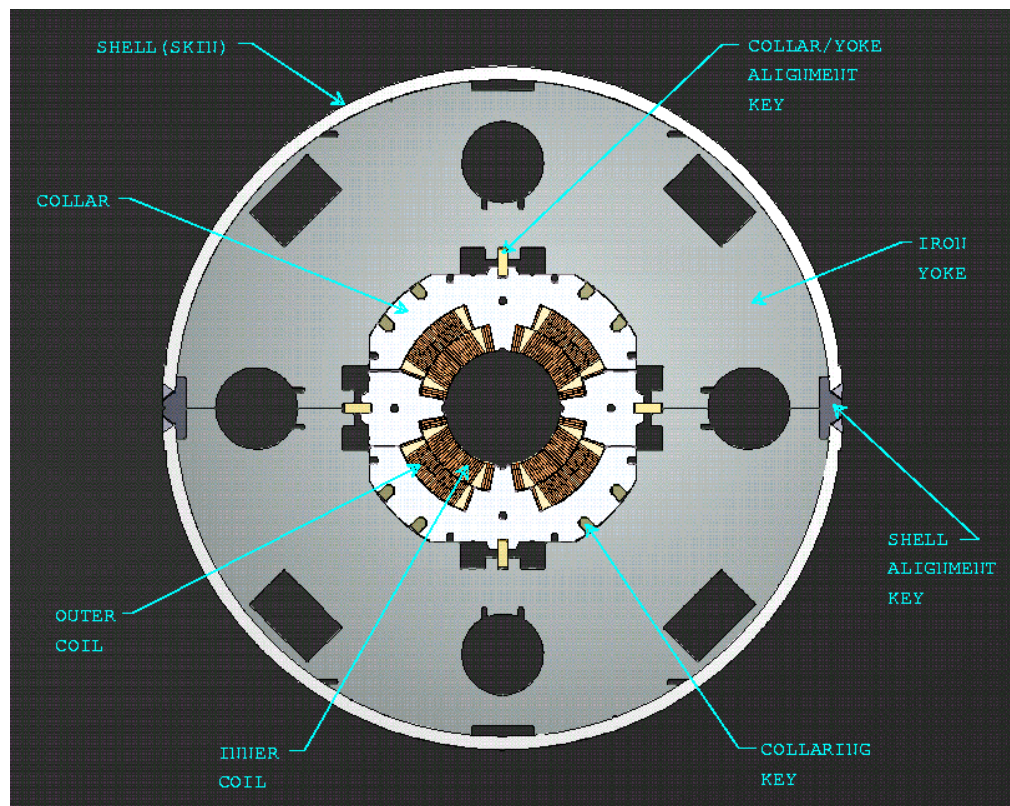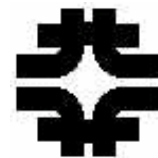
NbTi MQXB cross-section.

Two-layer NbTi coil with 70-mm bore, insulated with Kapton, supported by SS collar and surrounded by iron yoke.

Cold mass is filled by pressurized superfluid He at T=1.9 K.

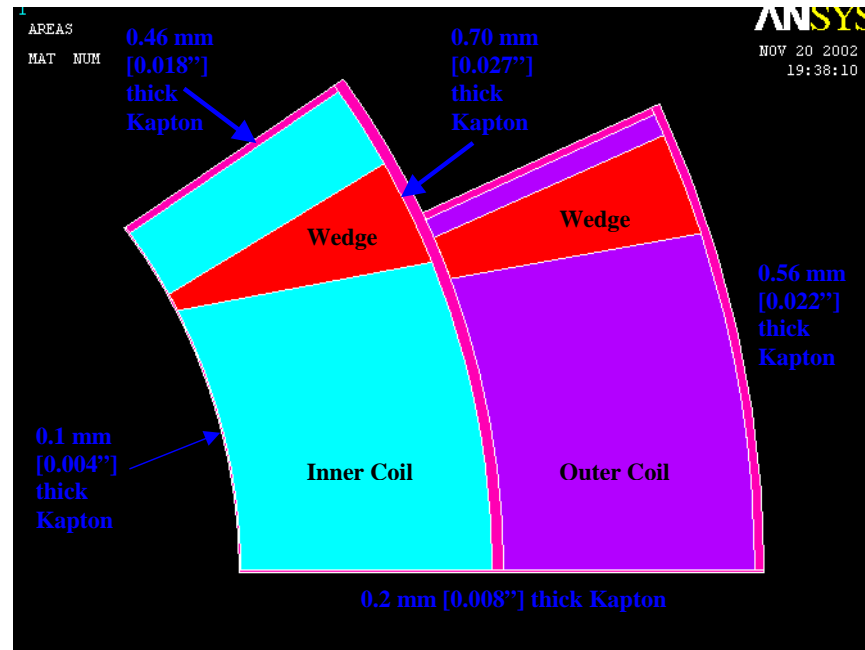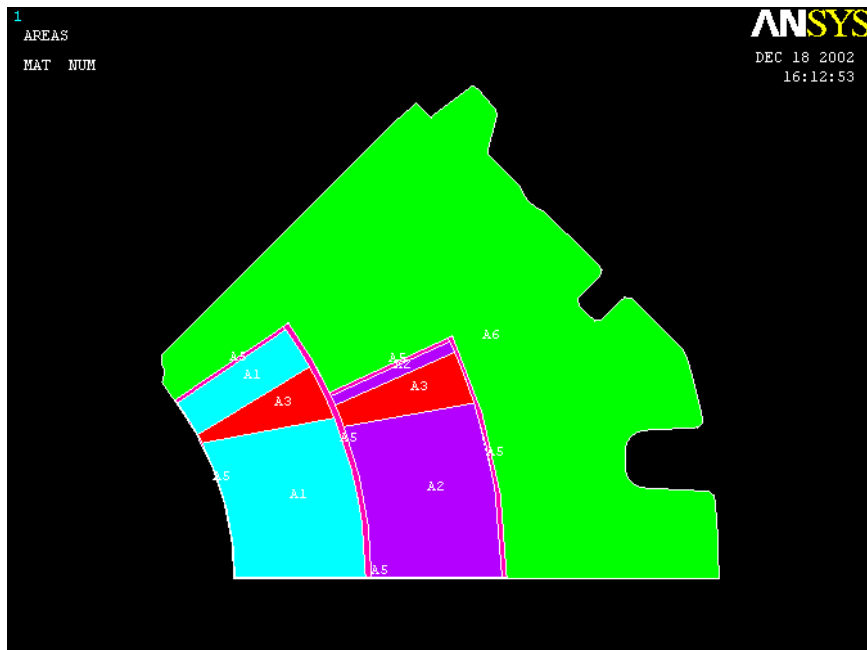External HeII heat exchanger connected with cold mass at each end.

Annular channel between the beam pipe and the coil – *longitudinal and azimuthal heat transfer*

Periodic radial channels in quad poles, porous collar and yoke blocks – *radial heat transfer*

Longitudinal channels in the iron yoke – *longitudinal heat transfer to the heat exchanger*

- Two-dimensional finite element thermal model of the collared-coil cross-section was developed using ANSYS code.

- It includes the inner and outer coil layers which consist of insulated cables and wedges, the ground insulation, and the stainless steel collars.

- The materials used in the modeled geometry are shown with different colors.
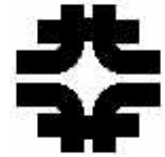
Material properties:

• Thermal conductivity at 1.9 K for different materials used in the magnet is summarized in Table.

• In this analysis it was assumed that the material properties are independent on temperature variation.

Material	Thermal Conductivity at 1.9 K (W/m/K)
Inner Coil Azimuthal	0.018
Outer Coil Azimuthal	0.016
Inner Coil Radial	4.54
Outer Coil Radial	6.45
Copper (wedges)	140
Kapton (insulation)	0.005
Stainless Steel (collar)	0.1

Coil cooling conditions:

• Boundary conditions include constant HeII temperature of 1.9 K in the annular channel and on the outer surface of the coil (or collar), and zero heat flux through the coil mid-plane.

• At the coil bore side, a constant heat transfer coefficient of 300 W/m^2/K was applied (Kapitza resistance).

• Calculations assumed that the space between the turns inside the coil and between the coil layers is closed (filled) by cable insulation.

• The case of cooling channels between the coil layers was modeled by applying a temperature boundary condition of 1.95 K between the coil layers.

NbTi MQXB: Radiation Heat Depositions
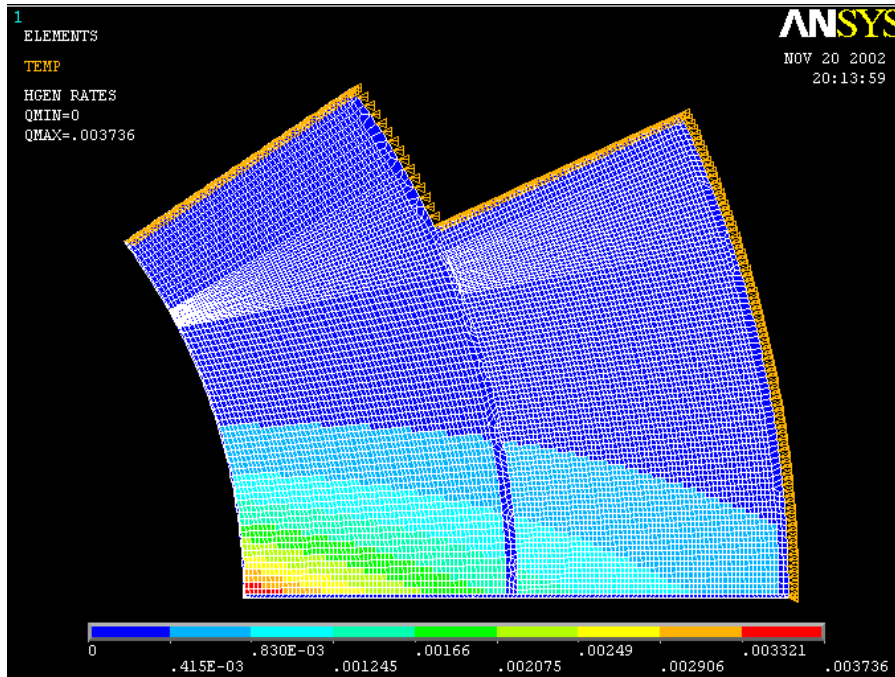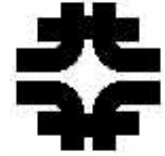
Contour plot of the applied heat load. There is strong dependence of radiation-induced heat depositions on radial and azimuthal coordinate.

The distribution of radiation-induced heat depositions in the coil was fitted by the following function found from the analysis of the heat deposition distribution in MQXB calculated by MARS code:

$$P(r,\vartheta) = Po \cdot \exp\frac{-(r-Rin)}{Ro} \cdot \frac{\vartheta o}{\vartheta + \vartheta o}$$

where

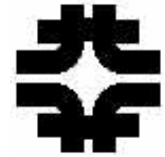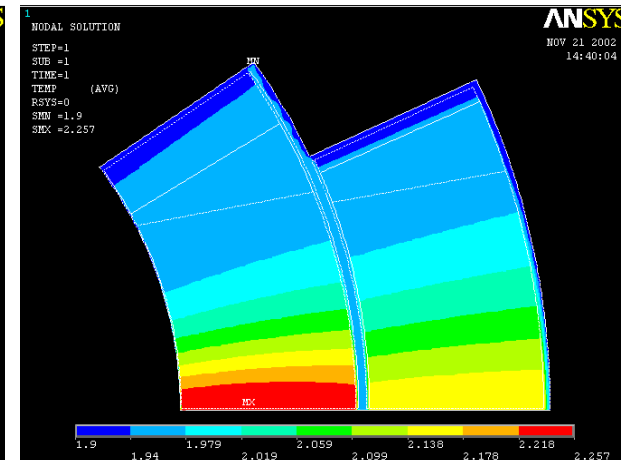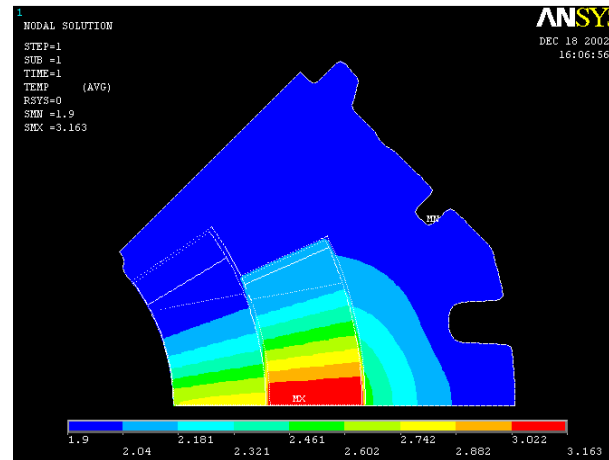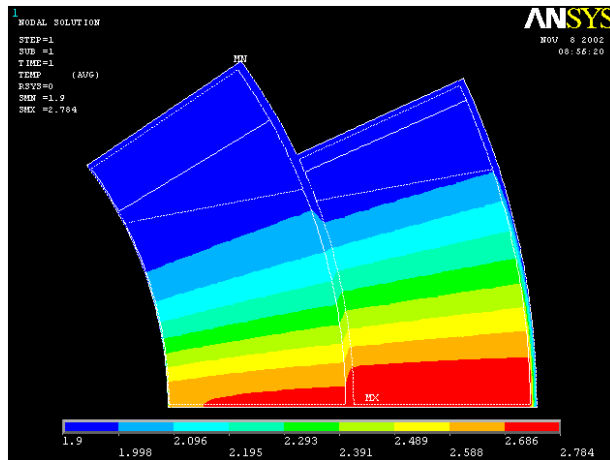 r and θ are polar coordinates,

Rin is the coil inner radius,

Po is the energy deposition power on the coil inner surface,

Ro and θo are fitting parameters.

NbTi MQXB: Temperature Profile

The calculated temperature profile for three cases:

- HeII penetrates inside the collar blocks reaching the coil outer surface
- HeII does not penetrate inside the collar blocks
- inter-layer HeII channel

The azimuthal temperature distribution in each layer is non-uniform due to low coil azimuthal thermal conductivity whereas the radial temperature distribution in each layer is quite uniform due to high radial thermal conductivity.

In all three cases the maximum temperature is in the coil mid-plane.

NbTi MQXB: Mid-plane Temperature

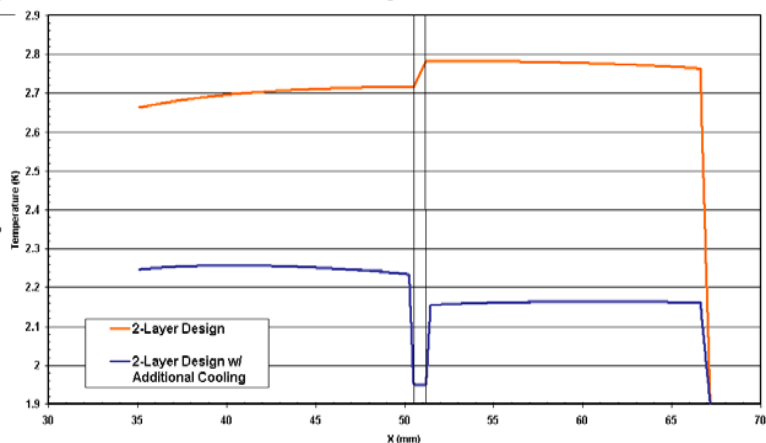Temperature distribution along the coil
mid-plane.
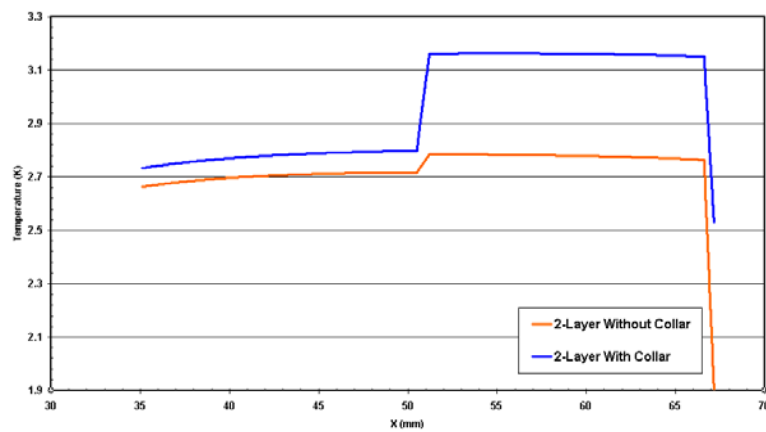
A larger temperature rise (especially in the coil outer layer) is observed for the case when superfluid Helium does not penetrate inside the collar blocks.

However, the effect is relatively small and general temperature profile remains the same with the coil T_{max} in the outer layer.
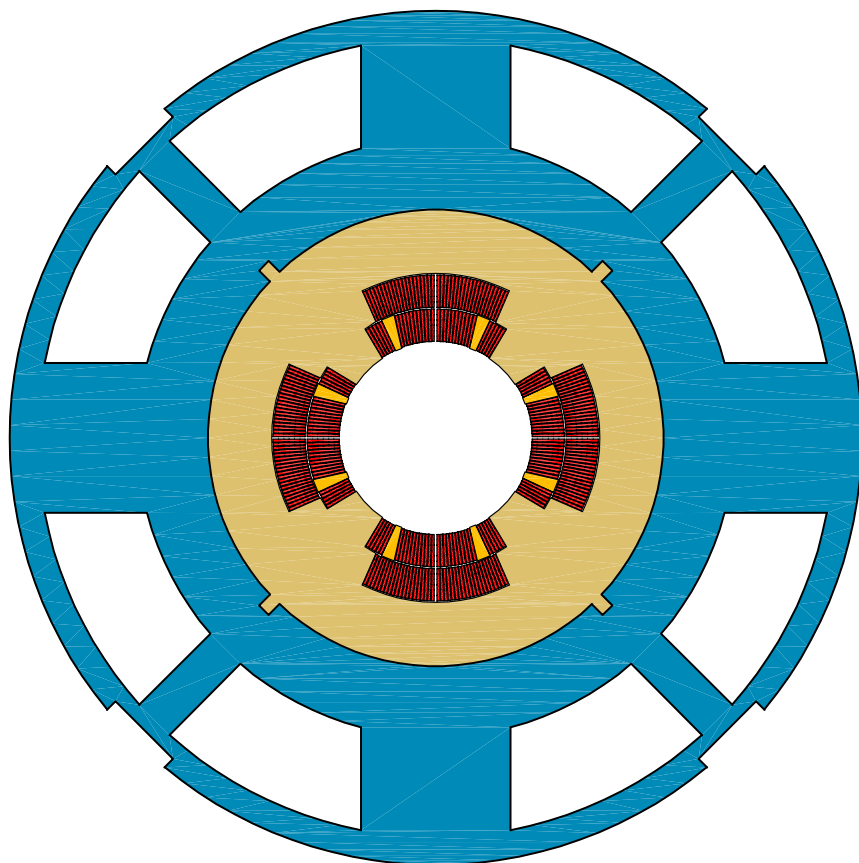
Interlayer cooling channel in two-layer coil allows significant reduction of the temperature of both layers.

The inner layer temperature decreases by ~450 mK and that of the outer layer by ~600 mK.

The coil T_{max} in this case moves to the coil inner layer.

Nb3Sn IRQ: Preliminary Magnet Design

90-mm Nb3Sn quads cross-section.

Two-layer Nb3Sn coil with 90-mm bore, insulated with thick S2-glass/epoxy insulation, supported by SS collar and surrounded by iron yoke.

Cold mass is filled by pressurized superfluid He at T=1.9 K.

External HeII heat exchanger connected with cold mass at each end.

Annular channel between the beam pipe and the coil – *longitudinal and azimuthal heat transfer*

Periodic radial channels in quad poles, porous collar and yoke blocks – *radial heat transfer*

Large longitudinal channels in the iron yoke – *longitudinal heat transfer to the heat exchanger*

IRQ NbSn thermal model, ID=45mm, OD=76.4mm, YIR=107mm
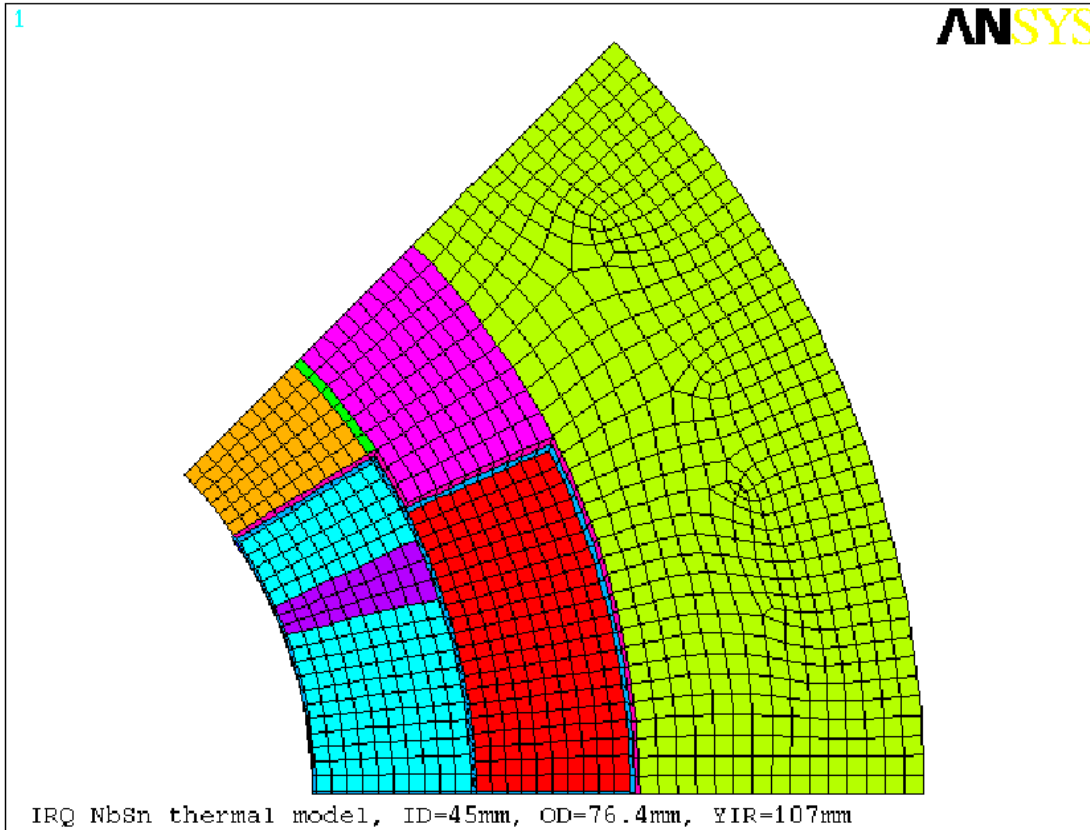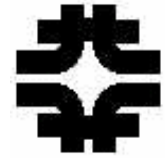
Two-dimensional finite element thermal model of the collared coil cross-section was developed using ANSYS code.

The model is based on the octant symmetry and includes inner and outer coils, ground insulation, aluminum-silicon bronze pole spacer and stainless steel collars.

The materials used in the modeled geometry are shown with different colors.
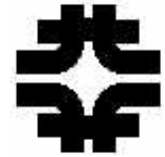
Material properties:

• Thermal conductivity at 1.9 K for materials used in the magnet design is summarized in Table.

• It was assumed that the material properties are independent on temperature variation.

| Material	Thermal Conductivity at 1.9 K (W/m/K)
Inner/Outer Coil Azimuthal	0.046
Inner/Outer Coil Radial	10.0
Bronze (wedges, poles)	0.8
S2-glass/epoxy (cable insulation)	0.03
Kapton (ground insulation)	0.005
Stainless Steel (collar)	0.1

Heat depositions:

• The distribution of radiation-induced heat depositions in the coil was fitted by the similar function found from the analysis of the heat deposition distribution calculated by MARS code (see slide 7).

Coil cooling conditions:

• Boundary conditions include constant HeII temperature of 1.9 K in the annular channel and on the outer surface of the coil (or collar), and zero heat flux through the coil mid- and pole planes.

• At the coil bore side, a constant heat transfer coefficient of 300 W/m^2/K was applied (Kapitza resistance).

Nb3Sn IRQ: Temperature Profile
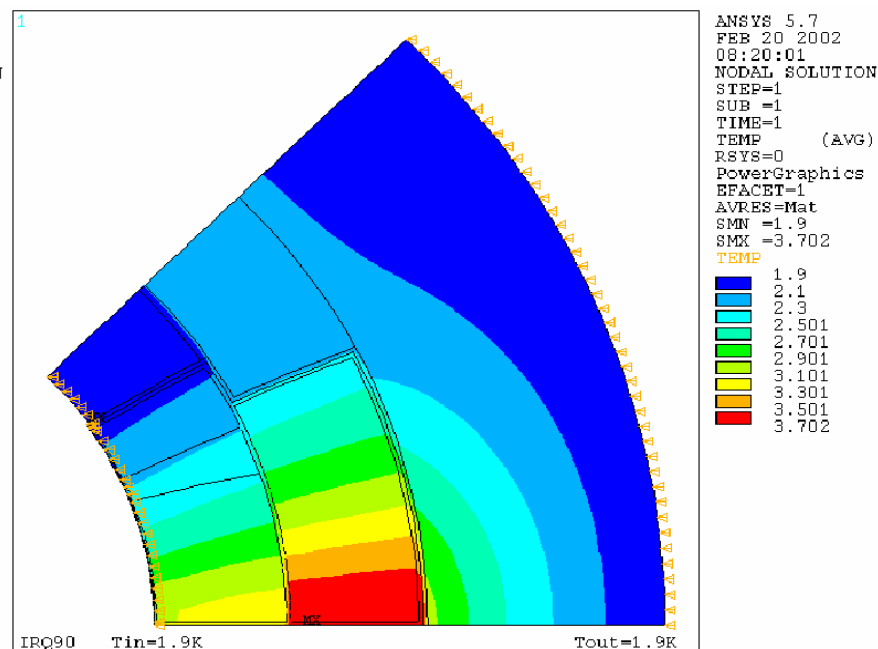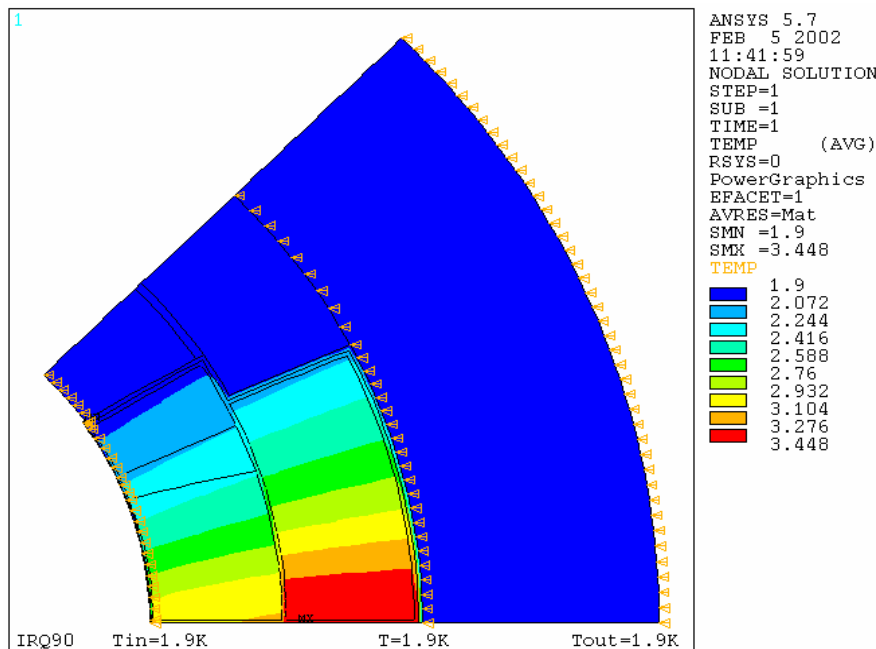
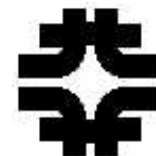The calculated temperature profile for two cases:

- HeII penetrates inside the collar blocks reaching the coil outer surface
- HeII does not penetrate inside the collar blocks

As in the case of NbTi quad the azimuthal temperature distribution in each layer is non-uniform and the radial temperature distribution in each layer is quite uniform.

In both cases the maximum temperature is in the coil mid-plane in the outer layer.
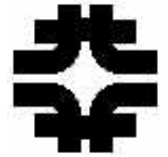
Nb3Sn IRQ: Midplane Temperature
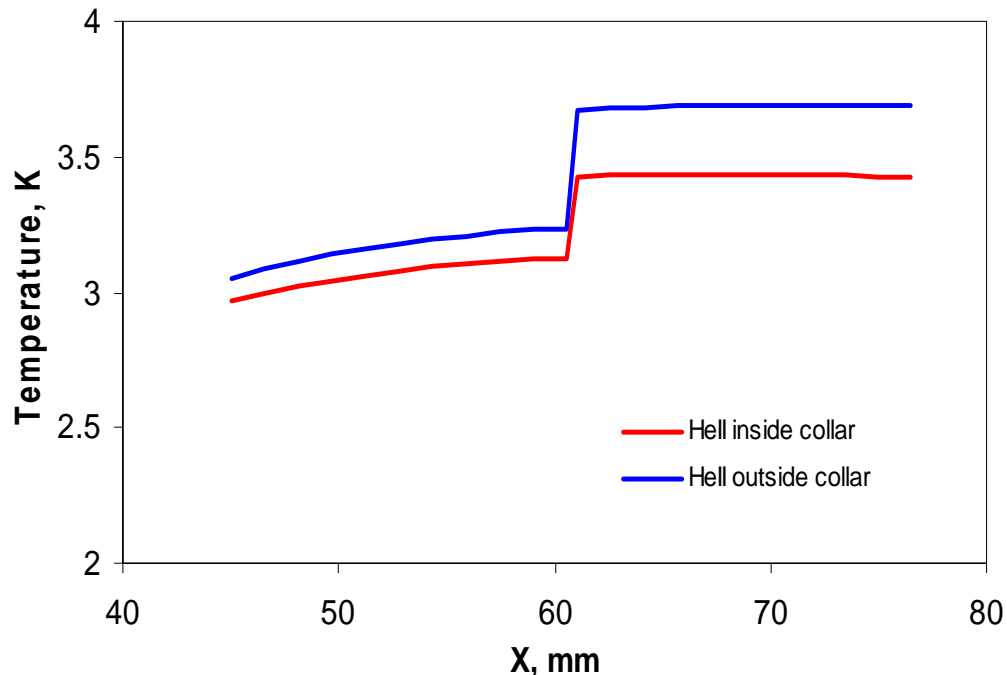
As expected, a larger temperature rise is observed for the case where the 1.9 K boundary condition is applied at the collar external surface.

However, the effect is small and the general temperature profile remains the same.

Temperature distribution along the coil mid-plane.

Summary of Thermal Analysis

The azimuthal temperature distribution in each layer is non-uniform and the radial temperature distribution in each layer is quite uniform in cases of NbTi and Nb3Sn IR quads, although both the radial and azimuthal distributions of radiation-induced heat deposition in the coil are non-uniform.

The temperature distribution for each turn is practically uniform.

In both cases the maximum turn temperature is in the coil mid-plane in the outer layer.

The turn temperature rise *dT* is determined by the average heating power *Pav* deposited in the turn

$$dT \sim k(Pav){\cdot}Pav,$$

where coefficient *k(Pav)* characterizes the turn cooling conditions in the coil.

Coefficients *k(Pav)* for each turn in magnet coil can be determined from the calculated temperature profile and known heat deposition distribution.

If material properties do not depend on *dT*, *k=const*, which depends on magnet design and turn position in the coil and.

Operation Margin Definition
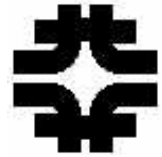
Turn Operation Margin (*TOM*) in magnet is defined as follows:

$$TOM_i = dT_{c\_i}/dT_{t\_i}$$

where

dT_{c_i} is turn #i critical temperature margin (depends on superconductor *Ic(B,T)*, operation current and temperature and turn position in a coil)

dT_{t_i} is turn #i temperature rise (depends on turn position in a coil – Pav_i, cooling conditions)

It could be defined also as

$$TOM_i = Pav_{c\_i}/Pav_{t\_i}$$

where

$Pav_{c\_i} = dT_{c\_i}/k$ is turn #i quench limit

Pav_{t_i} is average heating power in turn #i (e.g. MARS data)

Magnet Operation Margin (*MOM*) is defined as follows:
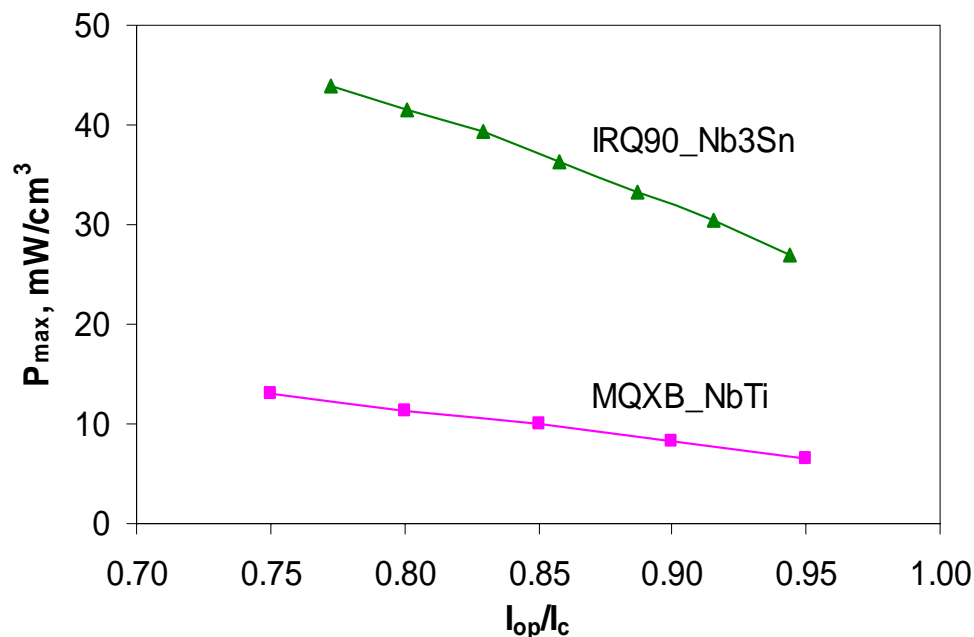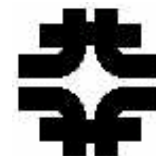
$$MOM = min(TOM_1, \ldots TOM_N),$$

where

N is the number of turns in magnet.

The operating margin of IR quads with respect to the radiation-induced heat deposition is determined by the operation margin of inner-layer mid-plane turn.

IRQ Quench Limit

Calculated quench limit for Nb3Sn IRQ and NbTi MQXB (inner-layer mid-plane turns) wrt the radiation heat depositions vs. the critical current margin at T_{op}=1.9 K.

Quench limit depends on superconductor $Ic(B,T)$, operation current (critical current margin), operation temperature and turn position in a coil.
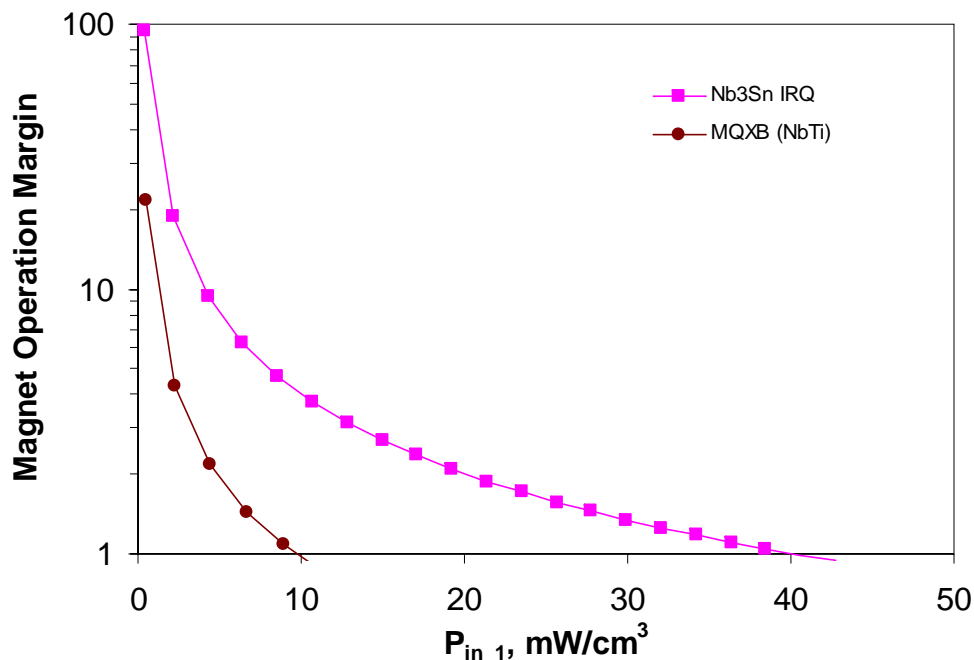
Quench limit at Iop/Ic=0.85 and Top=1.9 K

- 10 mW/cm^3 (NbTi MQXB)
- 36 mW/cm^3 (Nb3Sn IRQ)

Nb3Sn IR quads provide more than factor of 3 larger quench limit with respect to the radiation-induced heat depositions than NbTi IR quads (MQXB).

The effect of critical current margin is relatively small.

IRQ operation margin vs. the maximum energy deposition in the inner-layer mid-plane turn for the Nb3Sn IR quadrupoles and for the NbTi MQXB.

Energy deposition in the inner-layer mid-plane turn at the nominal LHC luminosity is 3.6 mW/cm^3.

NbTi MQXB quads at G_{nom}=205 T/m, T_{nom}=1.9 K and I_{op}/I_c=0.85 can operate at heat depositions in the coil a factor of ~2.5 higher than the nominal one.

Nb3Sn IR quads at G_{nom}=205 T/m, T_{nom}=1.9 K and I_{op}/I_c=0.85 can operate at heat load level a factor of 10 higher than the nominal one.

NbTi MQXB: Thermal Analysis Verification
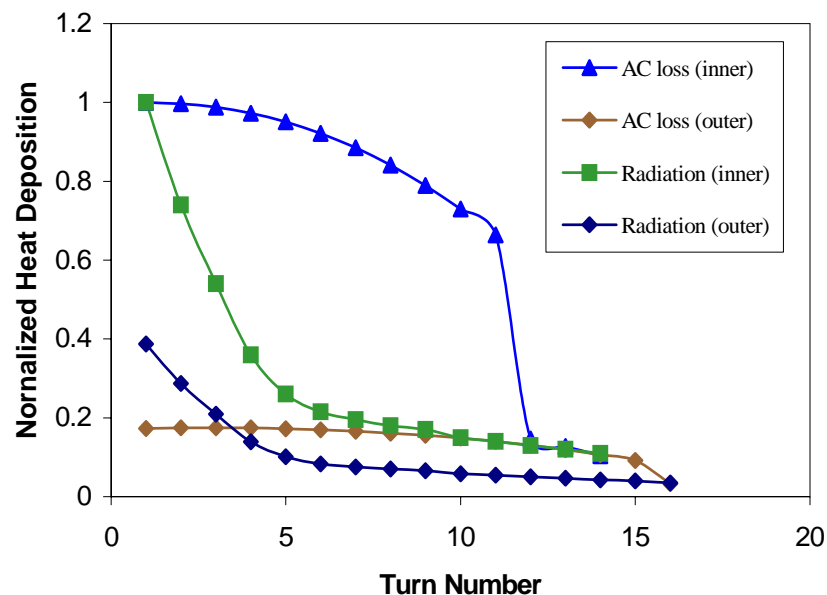
The calculated normalized AC loss distribution in HGQ08 coil. For a comparison the normalized distribution of the radiation heat deposition in the coil is also presented.

The motivation was to duplicate the high radiation heat loads predicted for the inner triplet quads at LHC and study the coil cooling conditions in the magnet.

AC losses vs. heaters

– Concerns about HeII penetration between turns

Experimental studies were performed using special HGQ short model (HGQ08) with high AC loss level in the coil.

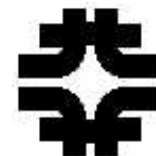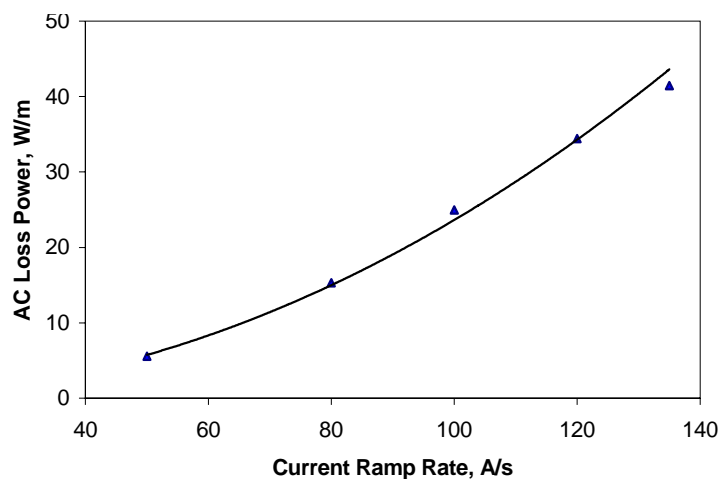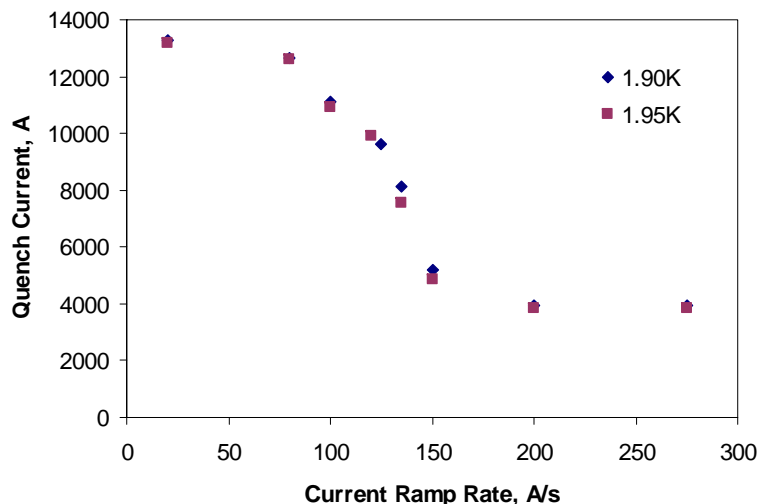A 2-m long model of an LHC IR quadrupole was wound with stabrite coated cable

– low and reproducible Rc

AC losses, as the radiation heat deposition, are maximal in the mid-plane turns of the inner layer.

AC losses are more uniformly distributed azimuthally in each layer than the radiation heat depositions.

The experimental verification of the HGQ thermal model is based on measurements of the sensitivity of the magnet critical current to the AC loss heat depositions in the coil.

The magnet quench current was measured as a function of the current ramp rate near the nominal field gradient of 205 T/m planned for the high luminosity interaction regions.

Quenches were detected in the mid-plane turns at dI/dt>75 A/s

AC loss measurements and calculated AC loss distribution in the coil provided a correlation between current ramp rate and heat deposition in the mid-plane turns.
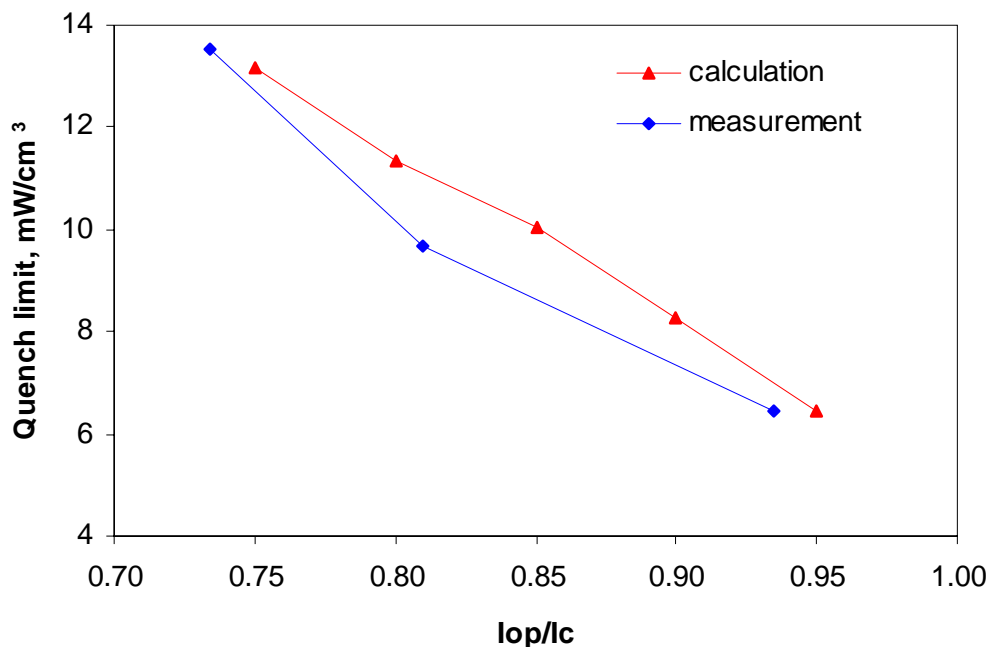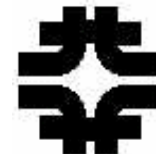
Measured and calculated quench limit for NbTi MQXB (inner-layer mid-plane turns) vs. the critical current margin at T_{op}=1.9 K.

Good correlation of measured and calculated data in case of blocked channels in the inner-layer insulation.

The blocking of turn cooling channels with insulation in the assembled magnet was also visually checked and confirmed in a mechanical model.
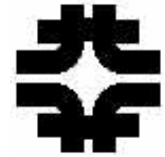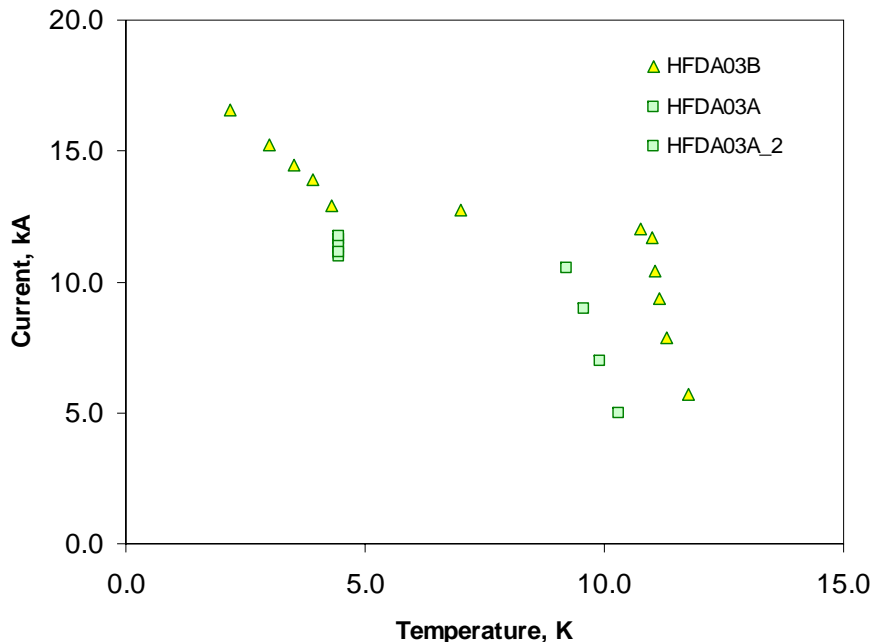
Quench limit at Iop/Ic=0.85 and Top=1.9 K

-10 mW/cm^3 (calculation)

-9-9.5 mW/cm^3 (measurement)

The experimental data confirm that MQXB IR quads provide the operation margin of ~2.5 wrt to the radiation heat deposition at the nominal LHC luminosity and Top=1.9-1.95 K.

Measurements of magnet quench current vs. heater temperature in HFDA Nb3Sn dipole models

Experimental measurements of the quench limit and operation margin for Nb3Sn IR quads is important.

AC losses vs. heaters

- difficult to determine with good accuracy the AC loss distribution in Nb3Sn coils due to large and uncontrollable variations of Rc in the coil

- possible to install resistive heaters on the mid-plane turn (positive experience with HFDA and HFDB Nb3Sn models at Fermilab at I/Ic>0.25)

Conclusions
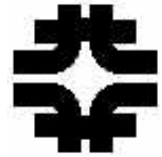
NbTi MQXB:

- Quench limit at Iop/Ic=0.85 and Top=1.9 K is 10 mW/cm^3 (calculation) and 9-9.5 mW/cm^3 (measurement)
- Factor of 2.5 operation margin wrt radiation-induced heat deposition at nominal luminosity

Nb3Sn IRQ:

- Quench limit at Iop/Ic=0.85 and Top=1.9 K is 36 mW/cm^3 (calculation)
- Factor of 10 operation margin wrt radiation-induced heat deposition at nominal luminosity
- Thermal analysis
    - Coil thermal conductivity measurements
    - Kapitza resistance for S2-glass/epoxy insulation
    - Temperature dependence of material properties
    - Sensitivity analysis (Bc2, Tc, stress, radiation, etc.)
- Experimental verification of the thermal analysis using Nb3Sn dipole models (available) or future IRQ models (work in progress)
- HeII heat exchanger for larger heat depositions in the magnets